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14. ABSTRACT

Sensing, modeling, and data analysis techniques for health monitoring of composite missile casings (carbon filament wound and S2 glass filament wound) have been developed. Here, the term “health monitoring” is used to refer to both loads identification and damage identification for the purpose of assessing the material state and structural performance of a missile casing pressure vessel. Impact loads were located and quantified using a single sensor without a detailed model of the casing through a combination of iterative least-squares calculations and cubic-spline interpolations based on a modal decomposition of the dynamic response. Damage was detected using only passive response measurements by analyzing the time-varying

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Report Title

Final Report: Evaluation of Impact Mitigation and Health Monitoring Tradeoffs in Composite Missile Casing Design Using Iterative inversion Loads and Damage Identification Methods

ABSTRACT

Sensing, modeling, and data analysis techniques for health monitoring of composite missile casings (carbon filament wound and S2 glass filament wound) have been developed. Here, the term "health monitoring" is used to refer to both loads identification and damage identification for the purpose of assessing the material state and structural performance of a missile casing pressure vessel. Impact loads were located and quantified using a single sensor without a detailed model of the casing through a combination of iterative least-squares calculations and cubic-spline interpolations based on a modal decomposition of the dynamic response. Damage was detected using only passive response measurements by analyzing the time-varying nature of the casing during a damaging impact. Damage has also been detected despite changes in test conditions based on nonlinear identification of modulation. The techniques have been transferred to AMRDEC and ARL in addition to the USMC an industry.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Stites, S. and Adams, D. E., "Minimal-Sensing, Passive Force Identification Techniques for a Composite Structural Missile Component," 2008, Shock and Vibration, in print.
2. Yoder, N. Muhammad, H. Adams, D. E., and Triplett, M., "Multi-Dimensional Sensing for Impact Load and Damage Evaluation in a Carbon Filament Wound Canister," (invited paper) 2008, Materials Evaluation, accepted for publication.
3. Stites, S. and Adams, D. E., "Semi-active damage identification for a composite structural missile component using minimal passive sensing with data-driven models," (invited paper) 2008, Smart Structures and Materials, accepted for publication.

Number of Papers published in peer-reviewed journals: 3.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

1. Stites, S., Escobar, C., White, J., Adams, D. E., and Triplett, M., "Quasi-Active Algorithm with Passive Sensing Techniques for Load and Damage Identification and Quantification in Filament-Wound Rocket Motor Casings using a Single Triaxial Accelerometer," 2007, Proceedings of the 17th U.S. Army Symposium on Solid Mechanics, Baltimore, MD.

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. Yoder, N., Zwink, B., and Adams, D. E., "Impact Loading and Damage Identification using Minimal Dynamic Sensing Strategies," 2008, Proceedings of the Society for the Advancement of Material and Processing Engineering, Long Beach, CA, in print. (2nd Best Paper Award at SAMPE 2008)
2. Stites, N., Escobar, C., White, J., Adams, D. E., and Triplett, M., "Quasi-Active, Minimal Sensing for Load and Damage Identification and Quantification Techniques for Filament-Wound Rocket Motor Casings," 2007, Health Monitoring of Structural and Biological Systems, San Diego, CA, Edited by Kundu, Tribikram, Proceedings of SPIE, Vol. 6532, pp. 65321E.
3. Stites, N., Adams, D. E., Ryan, T., and Sterkenburg, R., "Integrated Health Monitoring of Gas Turbine Engine Wire Harnesses and Connectors," 2006, Proceedings of the European Workshop on Structural Health Monitoring, Granada, Spain, pp. 996-1003.

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 3

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Nathan Yoder	0.25
Nick Stites	0.50
Jonathan White	0.25
FTE Equivalent:	**1.00**
Total Number:	**3**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Haroon Muhammad	0.25
FTE Equivalent:	**0.25**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Douglas Adams	0.15	No
FTE Equivalent:	**0.15**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Carlos Escobar	0.15
FTE Equivalent:	**0.15**
Total Number:	**1**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	1.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	1.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME	
Nick Stites	
Total Number:	**1**

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Final Summary for 50897-EG
Evaluation of Impact Mitigation and Health Monitoring Tradeoffs in Composite Missile Casing Design Using Iterative Inversion Loads and Damage Identification Methods
Principal Investigator: Douglas E. Adams, Purdue University

Forward

This document summarizes the approaches and accomplishments of the work conducted in missile case health monitoring under contract to the Army Research Office on Proposal Number 50897-EG. Sensing, modeling, and data analysis techniques for health monitoring of composite missile casings (carbon filament wound and S2 glass filament wound) have been developed. Here, the term “health monitoring” is used to refer to both loads identification and damage identification for the purpose of assessing the material state and structural performance of a missile casing pressure vessel.

Two types of health monitoring techniques have been developed:

- Passive techniques make use of only response measurements of a missile casing when it is acted upon by impacts or other forms of loading to identify loading and the damage it causes.
- Active techniques apply a separate vibration or acoustic stimulus to the casing and measure its response to heighten the measurement sensitivity to damage.

These techniques have been shown to:

- Passively detect, locate, and quantify transient loads (single or multiple impacts) with 99% accuracy with 5 cm resolution over 1000’s of impact experiments.
- Passively detect and quantify damage due to impacts using model updating that takes into account the time-varying nature of the dynamic response of a missile casing as it is loaded and becomes damaged due to cracking.
- Actively detect damage despite widely varying boundary and environmental conditions using nonlinear spectroscopy to identify modulation in the missile casing’s dynamic response due to cracking in its fibers.

Unique aspects of the work conducted to date include the following:

- Locate and quantify impacts using a single sensor without a detailed model of the casing through a combination of iterative least-squares calculations and cubic-spline interpolations based on a modal decomposition of the dynamic response.
- Detect damage to missile casings using only passive response measurements by analyzing the time-varying nature of the casing during a damaging impact.
- Detection of damage despite changes in temperature, humidity, and boundary conditions based on nonlinear identification of modulation due to cracking.

Description of Test and Analysis Specimen

Fig. 1(a) shows the carbon filament wound missile casing that has been investigated in detail. Fig. 1(b) shows the triaxial accelerometer that has been used to measure the passive response due to impact loading.

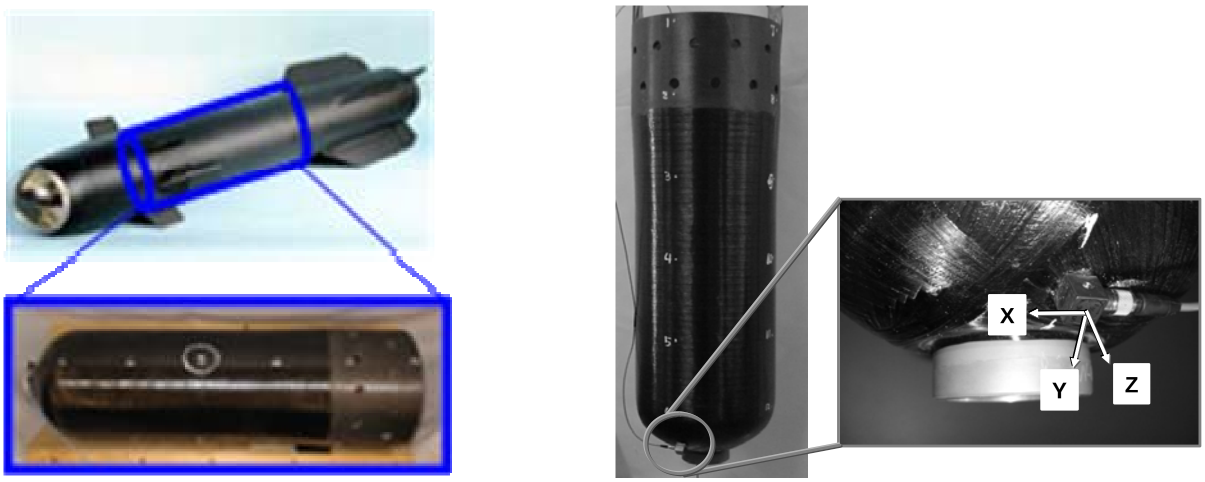

Figure 1 – (a) Carbon filament wound missile casing, and (b) triaxial accelerometer installed for measuring response.

Fig. 2 shows the Instron drop tower that has been used to apply and measure impulsive loads to the missile casing. This tower was purchased using funds from the Defense University Research Instrumentation Program in 2005. It is capable of 675 ft-lb impacts and has a tup sensor that measures the load and deflection upon impact.

Figure 2 – Instron drop tower used to simulate impulsive loads.

Summary of Most Important Results

Impact Identification

Fig. 3 shows a typical comparison of the estimated and actual applied force to a missile casing obtained using the passive load identification techniques that have been developed in this research. In these techniques, a frequency response function model that is developed for the casing is used to solve an underdetermined inverse problem in an iterative manner by enforcing constraints between the three response measurements that are made using the single triaxial accelerometer.

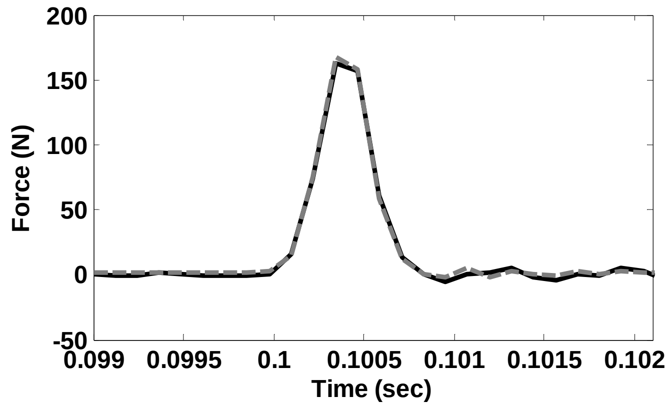

Figure 3 – Comparison of estimated (- - -) and actual (__) force time histories at a point on the casing.

Fig. 4 shows the typical results obtained when attempting to locate the impulsive loads on a missile casing. This contour plot indicates that the correct location of the impact has been identified. The frequency response model that was developed to locate the impact incorporated a small number of possible impact locations leading to a relatively small number of possible impact locations and coarse resolution in the estimated impact location. By applying cubic spline interpolation to the model in the axial direction and sinusoidal interpolation in the circumferential direction, an extremely fine resolution of impact locations every 5 cm can be resolved.

99% of the impacts applied across thousands of impact tests have been accurately located and quantified using these methods. Multiple impact events have also been accurately identified. A portable demonstration unit has also been developed and demonstrated at various technical conferences and expositions.

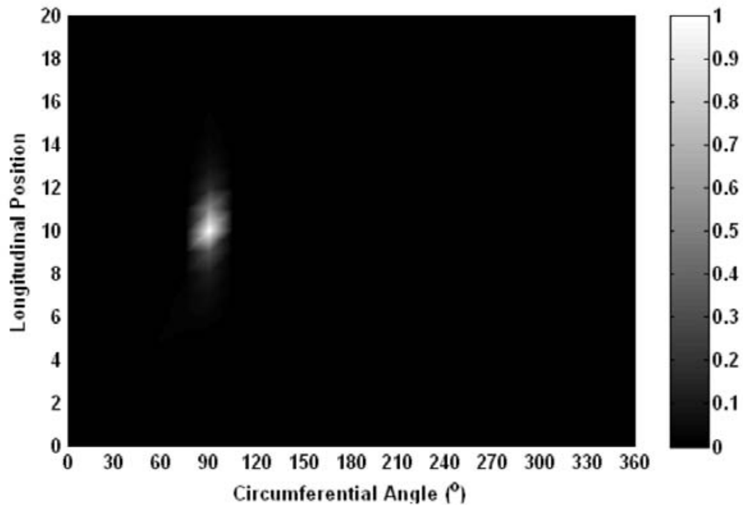

Figure 4 – Contour plot indicating the estimated location of an impact with high resolution using a low resolution frequency response model along with cubic spline interpolations.

Damage Identification (Passive)

Fig. 5 shows a typical crack produced using the Instron drop tower to apply an impact to a casing. Fig. 6 shows a comparison between three different frequency response functions. These frequency response functions relate the applied force at a single point on the casing to the measured response of the triaxial accelerometer in the direction normal to the surface of the casing. The plot shows that the healthy casing has a resonant frequency around 962 Hz (- - -) whereas the damaged casing has a 955 Hz resonant frequency (-.-).

Figure 5 – Crack produced in outer layer of fibers in missile casing.

During the impact event, a technique that was developed in this research was used to estimate an updated model of the casing using only the passive response acceleration measurements in three directions. When this technique was applied, the estimated frequency response function for the damaged casing (__) was obtained and indicated that there were two resonant frequencies in the measured response. During the first portion of the response, the casing was undamaged and exhibited the 962 Hz frequency whereas in the second portion of the response measurement, the casing was damaged and exhibited the 955 Hz frequency. This result demonstrates that passive response data can be used to detect damage in the casing due to impacts.

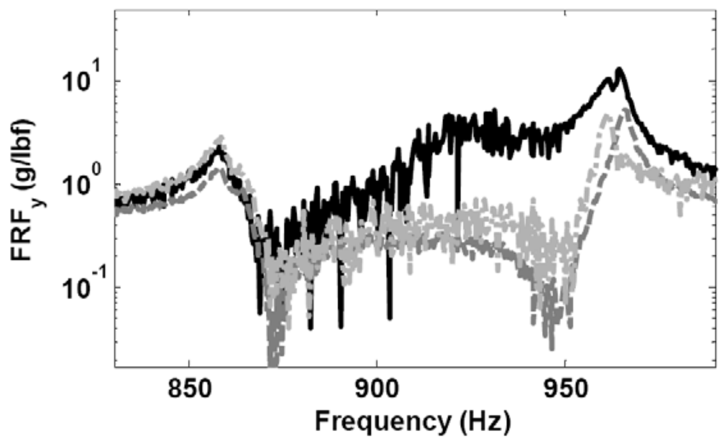

Figure 6 – Frequency response model relating input force at a given location measured in the healthy casing (- - -), measured in the damaged casing (-.-), and an estimate for the damaged casing (__) showing two resonant frequencies indicating that the casing has become damaged due to the impact.

To quantify the level of damage sustained during impact, the frequency shift, which was measured using only passive response data, was plotted as a function of the impulse in units of lbf-sec in Fig. 7. Note that for the online (passive) measurements, large impulse levels do not always lead to larger damage levels due to variations in the local stress field produced by impacts on the casings. **This result demonstrates that both force estimation and damage identification are needed to assess the condition of the missile casing.**

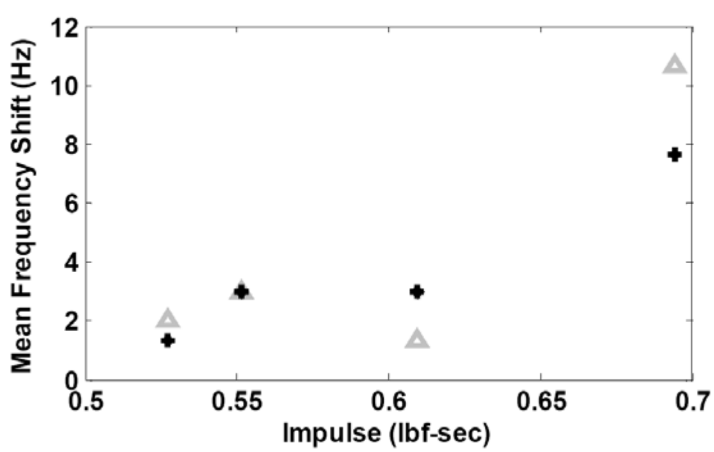

Figure 7 – Plot of frequency shift vs. impulse for offline inspections (Δ) and online measurements (*) indicating that larger impulses do not always lead to more damage due to variations in local stress fields upon impact.

Damage Identification (Active)

The online methods of health monitoring described above provide useful information related to the condition of the casing; however, if further inspection is warranted, an offline method of nondestructive testing must be applied. In practice, there is variability in the way in which the casing is installed in the missile system including the insertion of propellant. There is also variation in the temperature, humidity, and ambient vibration conditions under which the casing is tested. To reduce the sensitivity of an offline damage detection method to these sources of variation, a vibro-acoustic method for damage detection was developed. In this method, it is assumed that damage introduces nonlinearity in the response of the casing. A high frequency piezo actuator is attached with wax and drives the casing at 60 kHz. Then a modal tap hammer is used to excite the casing. If the casing is damaged due to cracking of the outer fibers, modulation between the high frequency response (carrier) and low frequency response (modal vibration) is observed. This phenomenon is referred to as impact modulation.

Fig. 8 shows the response spectra measured for an undamaged casing (far left) and damaged casing (remainder of the plots) using a 60 kHz carrier excitation signal along with modal tap testing and a single accelerometer measuring the response circumferentially. Note that the damage is detected via the modulation around 60 kHz regardless of the test conditions (when casing is stuffed with foam to simulate propellant or stuck in a freezer to simulate a change in both temperature and humidity).

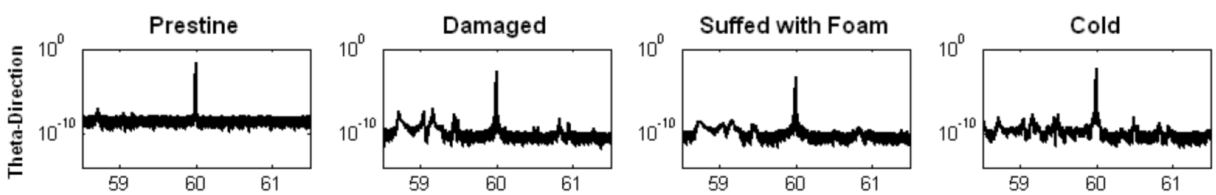

Figure 8 – Undamaged and damage casing acceleration spectra in the circumferential measurement direction for various testing conditions showing that damage is still detected via the modulation observed around the 60 kHz carrier frequency.

Impact Resistance

In addition to developing health monitoring techniques in this research, the impact resistance of carbon filament wound missile casings was also ascertained using impact testing in conjunction with high-speed camera photography.

Over a dozen cylinders with different winding configurations have been tested. The camera is focused on the impact zone and indicates the deformation pattern upon impact. The initial hypothesis was that highly localized impact deformation patterns (dimple type impact) would lead to more fiber breakage than distributed patterns due to the higher stresses in the case of localized deformation. The stress in the outer fibers in this case would be equal to σ=Mh/I where M is the bending moment applied to the cylinder wall, I is the cross-sectional area moment of inertia, and h is half the thickness of the case.

This hypothesis has been verified in experiments using a spherical impact head. For example, Figure 7 shows the impact zones for a cylinder with Kevlar overwrap (a) and a cylinder with carbon fibers (b) in the case of a 10 ft-lb impact. The Kevlar cylinder experienced significant cracking resulting in a lower burst pressure whereas the carbon fiber cylinder experienced less cracking due to the way in which the cylinder distributes the impact load all along the cylinder wall.

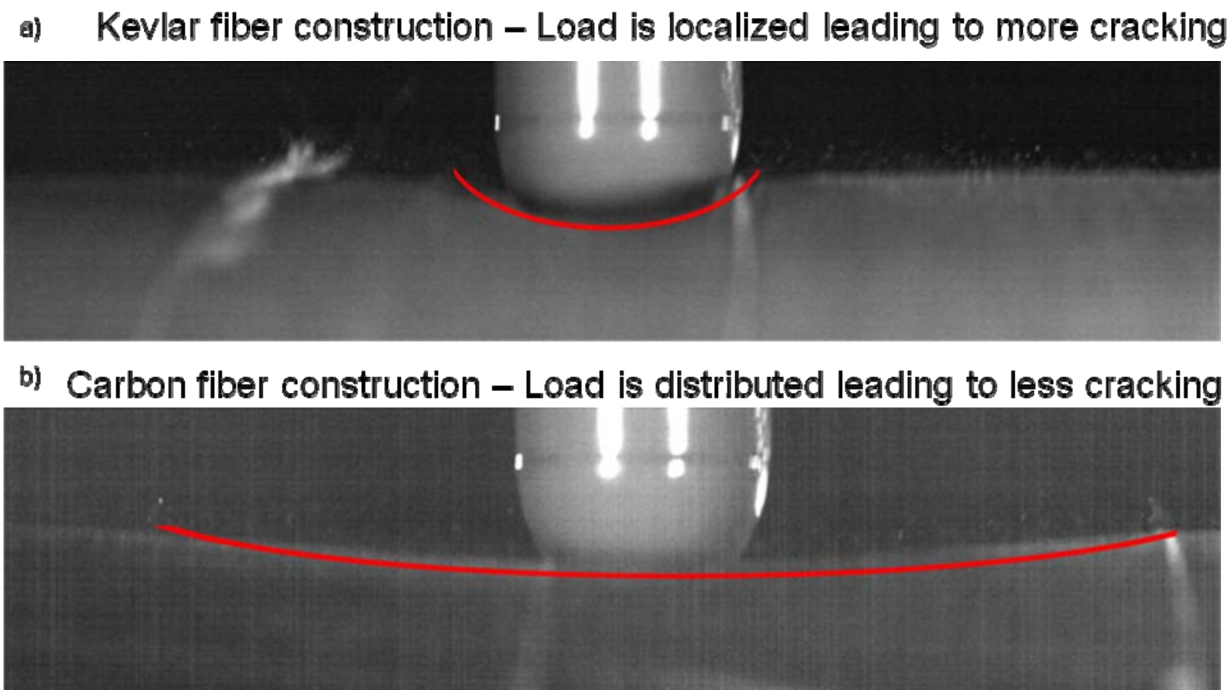

Figure 7 – Impact deformation patterns of two different cylinders.

Technology Transfer

The Principal Investigator has engaged in the following technology transfer activities over the course of this research.

- The Principal Investigator and his graduate research assistant have interacted on a weekly basis to discuss technical results on this research with two researchers from the Aviation and Missile Research and Development Engineering Center. Several reports have also been submitted to Army researchers and collaborative papers have been published.
- The Principal Investigator met three times with Mr. Triplett from the Aviation and Missile Research and Development Engineering Center to discuss the measurement approach and specimens to be used in this project. During one of

these meetings, Mr. Triplett and Mr. Esslinger visited Purdue University along with the prime contractor for the next generation Hellfire missile from Lockheed Martin to discuss this research program. The intent was for Lockheed Martin to evaluate this technology for possible development in their missile design.

- The Principal Investigator is transferring the technique for load identification to the US Marine Corps for use in helicopter rotor blades to identify impacts. By identifying impact loads on the blades, offline inspections of the blades can be reduced leading to greater aircraft availability in heavy-lift helicopters (CH-53).
- The Principal Investigator has also transferred this load identification technique to Rolls-Royce who is evaluating the method as a means of identifying extreme loads to wire harness connectors in gas turbine engines.
- The Principal Investigator wrote and taught a 500+ page short course on structural health monitoring in October 2006 to defense contractors at Lockheed Martin and researchers at NASA Dryden in Palmdale, CA as a part of the Purdue Professional Education program. Results from this ARO-sponsored research were discussed and a filament wound canister was used as a live demo during the course.
- The Principal Investigator delivered the keynote address at the Lightweight & Advanced Materials for Defense Workshop on June 27, 2006 in Alexandria, VA to describe the approaches being used in this research and transfer technologies developed on this and other research funded by the U.S. Army and U.S. Air Force to the defense industry (Lockheed, Boeing, General Dynamics, etc.).
- The Principal Investigator attended a workshop at Los Alamos National Laboratory on Health Monitoring in July 2006. During the workshop, the proposed research and results to date were described to personnel from Sandia National Laboratory, Los Alamos National Laboratory, The Boeing Company, and other organizations involved with the defense industry.

References

1. Adams, D. E., “Health Monitoring of Structural Materials and Components,” 2007, John Wiley & Sons, Chichester, U.K.
2. Stites, S. and Adams, D. E., “Minimal-Sensing, Passive Force Identification Techniques for a Composite Structural Missile Component,” 2008, *Shock and Vibration*, in print.
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